ROTATIONAL RESONANCE VIBROMETRY ON CERAMIC COMPONENTS

C.A. Döttinger and G. Busse
Institut für Kunststoffprüfung und Kunststoffkunde (IKP)
Universität Stuttgart
Pfaffenwaldring 32
70569 Stuttgart / Germany

INTRODUCTION

Let us assume an isotropic solid with rotational symmetry. If a pulse is injected normal to the surface, this excitation will result in a vibration along the same direction. This is true for any point around the circumference: The rotational symmetry of geometry and material results in a „rotational symmetry" of the response. If the sample is rotated by an arbitrary angle between two measurements, one finds always the same result.
As a consequence, reduction of symmetry (e.g. presence of defect, anisotropy of material, non-rotational geometry) causes an anisotropic response: In most cases the response is a superposition of two oszillations: A resonance split (Fig. 1b).

Figure 1(a-c) shows the overall resonance of one component with reduction of rotational symmetry by a defect. An accidental rotation of the sample may result in a totally different signal shape and a subsequent different interpretation.These measurements demonstrate also that an existing resonance split is not always detectible. On the other hand, the spectral effect of symmetry disturbance is useful to characterize a defect by the frequency split caused by it.

The theoretical and experimental investigations presented in this paper were performed in order to see how well the superposition of two harmonic oscillators describes the experimental results.

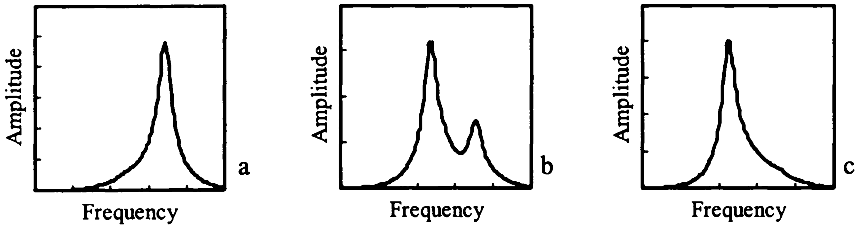

Figure 1a-c. Appearance of the overall resonance at different measurements of one component with reduction of rotational symmetry by a defect.

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 18
Edited by Thompson and Chimenti, Kluwer Academic/Plenum Publishers, 1999

THEORETICAL MODEL AND EXPERIMENTAL ARRANGEMENT

Theoretical Model

In the case of a component with rotational symmetry of properties and consistence of material which is described by Hooke's law, the harmonic oscillator (defined by its resonance frequency and damping) is a sufficient model. The coordinates of the sample with rotational symmetry could be chosen arbitrarily (Fig. 2a).

If the system is no longer symmetrical in terms of e.g. presence of a defect, there is a preferential orientation of the coordinate system with respect to the defect. The directions are no more equivalent. There are rather two main directions, two independent sets of mutually perpendicular directions of oscillation. The injection of a pulse orthogonal to the surface results in oscillations parallel to these main directions.
In this case the approximation are two harmonic oscillators with different resonance frequencies. Therefore the excitation must be decomposed into two components along the defect coordinate system where each direction has its own response. The response vectors are subsequently added and projected into the out-of-plane direction (Fig. 2b).

So there are two frequencies involved with a difference that is given by the nature and the size of the defect, while the overall resonance depends on the mixture and therefore on the direction of excitation. That is why the resonance curve appears different when the sample is rotated (Fig. 1a-c).

With this approximation magnitude and phase are calculated as a function of frequency and rotational angle.

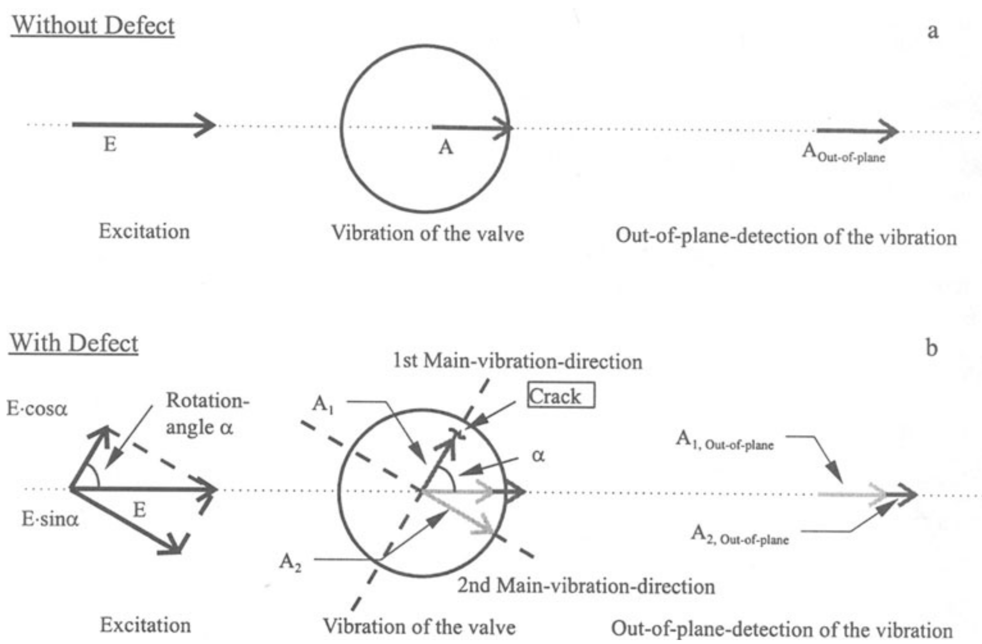

Figure 2a-b. Preferential orientation of the coordinate system with respect to a defect in a component with rotation symmetry (decomposition of the excitation and addition of the vibration in the out-of-plane direction).

Though this separation of orthogonal vibrations is similar to the principle applied to Lissajous patterns, it is important to note that in our case the frequency ratio may be very close to one, also the phase difference between the two oscillations is determined by the excitation frequency.

Experimental Arrangement

For the experimental setup it is important that the frequency response can be monitored over a certain range. Though mechanical response spectroscopy is well known since some time [1,2], any technique based on the attachment of a sensor or a transducer is not applicable since its effect on the response of the system is expected to be stronger than the small splitting induced by the defect. In fact, such a mechanical coupling [3] would set the noise equivalent defect size to unacceptable values. Therefore we performed mechanical spectroscopy without any physical contact of the transducer with the sample under inspection.

The experimental setup is shown in Fig. 3: A loudspeaker coupled to a tunable generator provides a unidirectional sine-wave acoustic excitation of the valve [4]. This way the problem of input coupling is avoided. Detection of the vibration must also be performed without affecting the symmetry [5,6]. Therefore one has to use a sensor with zero mass and without mechanical contact, which is possible with a laser vibrometer whose principle is based on interferometric detection (Polytec OFV 303/ OFV03001). This way the vibration is monitored at a certain small spot (0.1 mm diameter) and along a certain direction. The vibrometer signal is analysed with respect to phase and magnitude [5,6] while the frequency is swept at various rotational angles. The inspected component is hanging on one thin thread (100 μm diameter) attached to the top end of the symmetry line.

RESULTS

Amplitude and phase shift as calculated and observed are presented in Fig. 4 (amplitude) and Fig. 5 (phase shift).

In the case of rotational symmetry, the peak in the amplitude would be totally independent of the rotation-angle α and the phase shift surface in the α - f - plane would be just one soft step at a certain frequency whose width depends on damping. However, in the case of resonance splitting there must be 4 peaks in the amplitude and two steps in the phase shift that alternate with the rotational angle α.

It is obvious that experimental and theoretical curves agree. So the behavior of a ceramic component whose roational symmetry is reduced by a defect is well described by two mutually perpendicular harmonic modes.

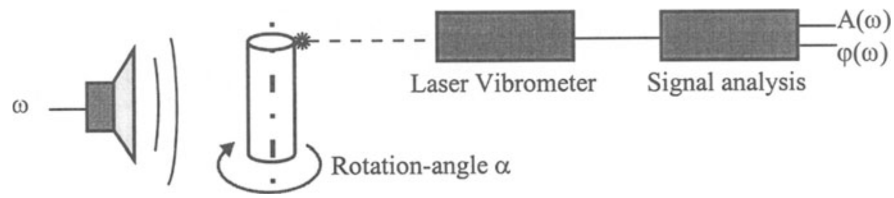

Figure 3. Experimental arrangement for acoustic spectroscopy of rotational symmetric components to provide frequency dependence of amplitude (A), phase (φ), and rotation-angle (α).

In the phase shift diagram the lines of equal rotation angle α display an interesting difference between high and low frequencies resulting in an S-shape at certain angles (especially at 45°).

It should also be noted that the amplitude curves reach nearly zero between the resonances since the high frequency side of the low frequency vibration is opposite in phase to the low frequency side of the high frequency vibration. At 45° both amplitudes are equal and hence cancel almost to zero.

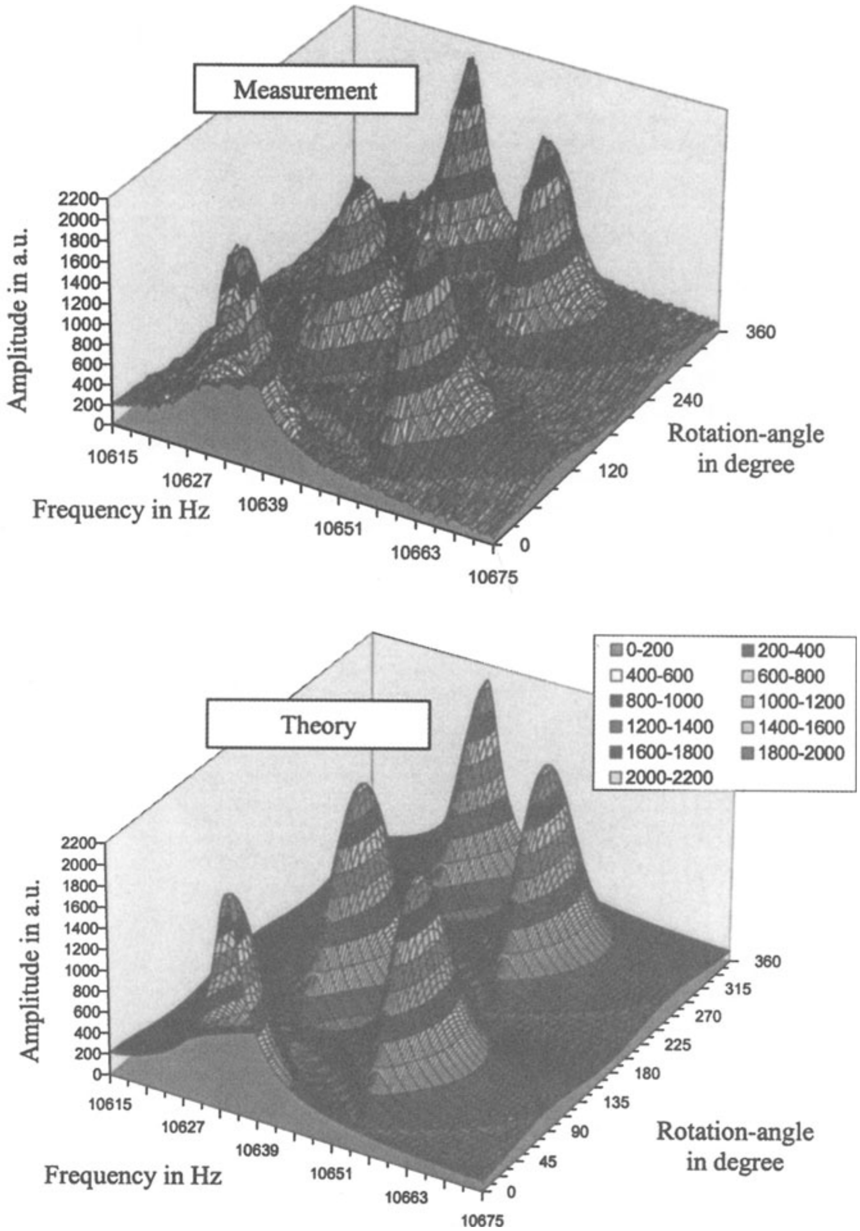

Figure 4. Vibration amplitude of a component with reduction in symmetry by a defect: Measurement compared to theory.

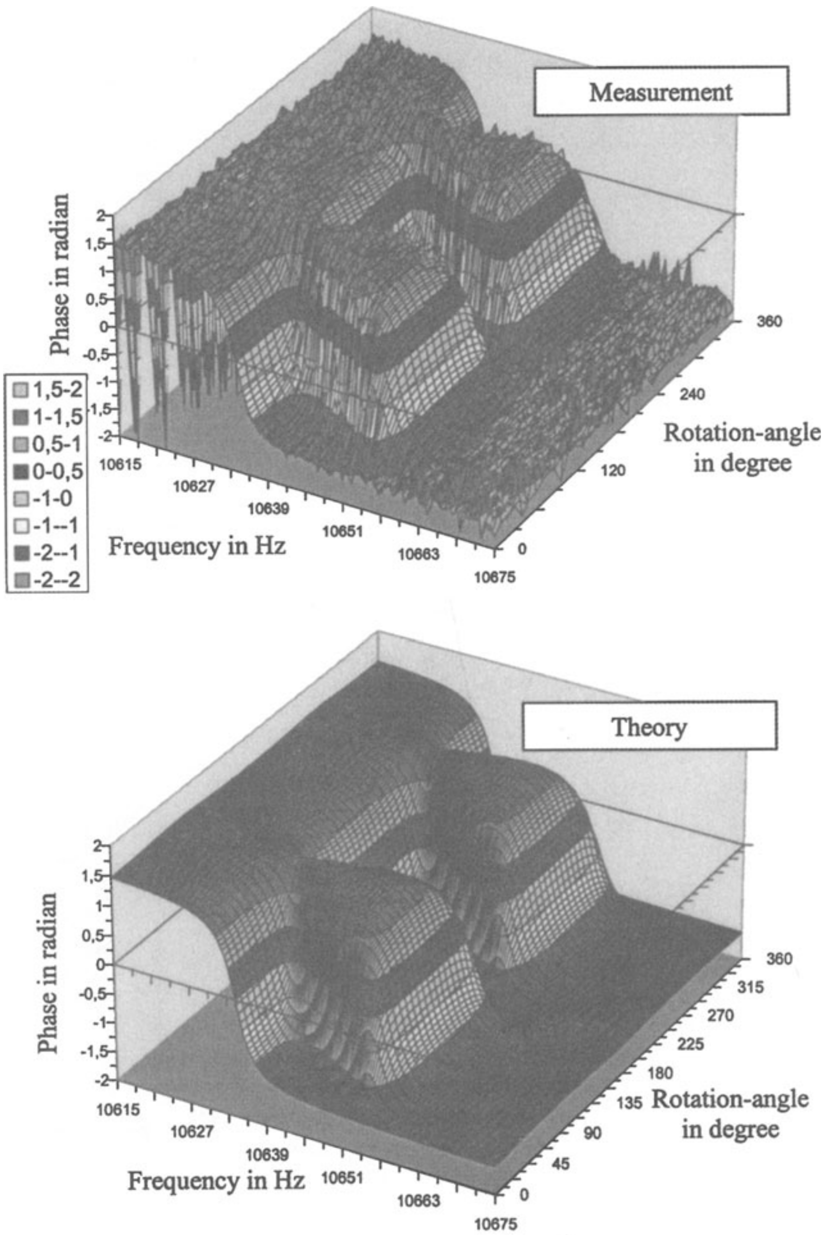

Figure 5. Phase shift in the vibration of a component with reduction in symmetry by a defect: Measurement compared to theory.

On the base of this agreement we investigated theoretically how the signal surface structure changes as the defect and its influence becomes smaller. Obviously the 4 maxima in Fig. 4 must move towards each other along the frequency axis. Fig. 6 shows the result for a situation where the splitting is about the halfwidth of the resonance peak in one of the main directions. The two cross sections show that only at 45° there are two clear maxima while at 22.5° the influence of the weaker component is seen just as a minor bump on one side of the resonance. This is the reason for the different appearances in Fig. 1.

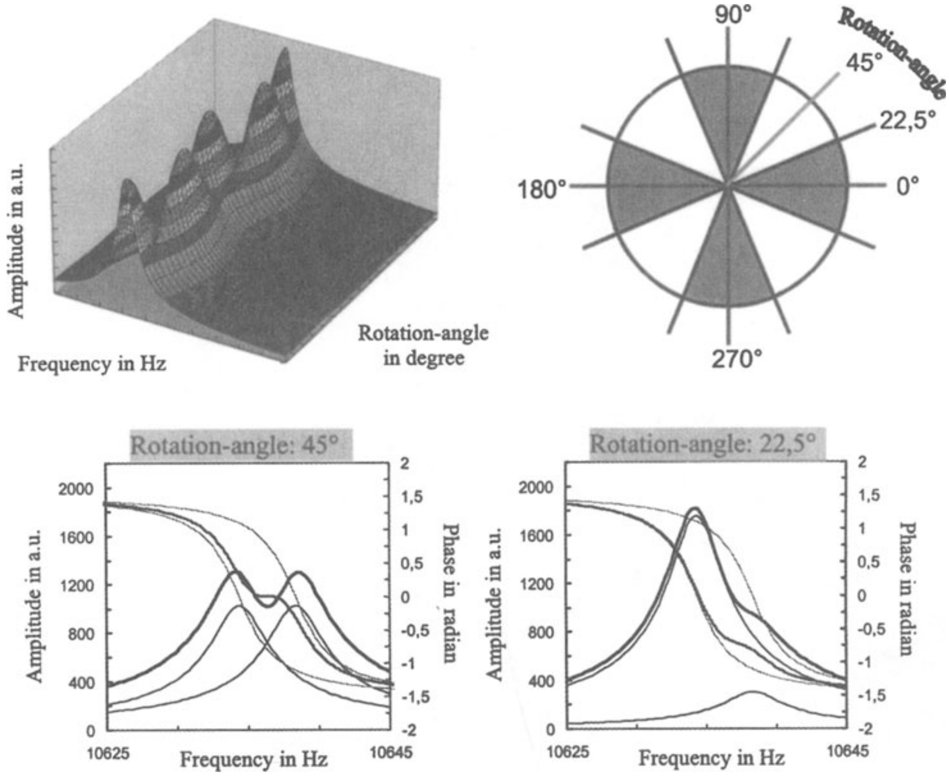

Figure 6. Reduction of the resonance splitting if the defect and its influence becomes smaller. Cross sections under 45° and 22.5° rotation angle α ($\pm$ 22,5° regarding main directions are terminating "blind segments").

It is evident that the angular segment of rotation α where seemingly only one resonance is observed increases with noise and with decreasing defect size.

Obviously one needs to perform at least 3 frequency scans at angles differing from each other by 22.5 ° in order to have a chance that one angle is not contained in the "blind segment" (shaded area in Fig. 5).

SUMMARY AND CONCLUSION

Our results confirm that high resolution acoustic spectroscopy of objects with rotational symmetry can be performed in such a way that one observes the lifted degeneracy thereby revealing the presence of anisotropy caused by defects (e.g. cracks, void, texture of material).

This is a powerful method to characterize the quality of safety-relevant ceramic components. The primary results obtained from such measurements are the frequency split and the damping. Though these data can serve as monitors for a constant production quality, the final goal is to characterize the kind of defects from such data.

ACKNOWLEDGEMENTS

This work has been sponsored by the Deutsche Forschungsgemeinschaft DFG (Transfercenter TFB 4).

REFERENCES

1. Cawley, P.; Adams, R.D.: Vibration Techniques. In: Summerscales, J.:Non-destructive testing of fibre-reinforced plastics composites. Volume 1. London: Elsevier Applied Science, 1987.
2. Adams, R.D. and Cawley, P.: Vibration techniques in nondestructive testing. Research Techniques in NDT R.S. Sharpe (ed) 8 (1985) pp. 303-360.
3. White, R.M.: Generation of elastic waves by transient surface heating. In: J. Appl. Phys. 34 (1963), pp. 3559-3567.
4. Biwas, A.; Weller, T.; Katehi; L.P.B.: Stress determination of micromembranes using laser vibrometry. In: Rev. Sci. Instrum. 76 (1996), pp.1965-1969.
5. Lyamshev, M.L.; Stanullo, J.; Busse, G.: Thermo acoustic vibrometry. Remote „in situ“ monotoring of ceramic sintering. Materialprüfung 37 1-2 (1995), Carl Hanser Verlag, München, pp. 22-24.
6. Döttinger, C.A.; Stanullo. J.; Lyamshev, M.L.; Busse, G.: Remote vibrometry for characterisation of materials and processes. 5th International Congress on Sound and Vibration. University of Adelaide, 15.-18.12 1997.